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DYNAMIC RESPONSE ANALYSIS OF A TABLE TOP COMPRESSOR FOUNDATION

ANALÝZA DYNAMICKÉ ODEZVY ZÁKLADŮ PRO COMPRESOR

Abstract

Dynamic response analysis of a table top type foundation for a large centrifugal compressor destined for a plant in an earthquake endangered area has been carried out using FE computation model. The soil-structure interaction has been considered by including the subsoil body into the model. The foundation design has been optimized with respect to severe restrictions of vibration intensity. Both steady state and transient responses to forces due to unbalances have been computed. Seismic response has been computed using the linear response spectrum method.

Key words: dynamic response analysis, numerical analysis

Introduction

Complex dynamic analysis constitutes the main background for a correct design of a "table top" type reinforced concrete foundation structure for a large centrifugal compressor with the driving unit. The vibration exciting forces have frequently high values and simultaneously, low levels of vibrational response are requested. Analyses based on simplified computation models (e.g. as shown in DIN 4024 - Part 1; DIN 4024 - Teil 2; Arya et al., 1979) provide incomplete design background. In order to get reliable knowledge of the dynamic behaviour of the designed foundation, a computation model of the analyzed structural system should be developed enabling the correct description of all involved mechanical processes. First of all the foundation structure with the driver-compressor system should be appropriately modeled with respect to its essential mechanical properties. Secondly, the soil-structure interaction should be modeled, particularly in cases, when the geological and geotechnical site conditions are unfavourable. In the analyzed case, the soil-structure interaction has been considered by including the subsoil body into the computation model. Correct determination of the dynamic response of the structural system to the defined excitation requests an appropriate description of the dissipation process. The excitation of structure vibrations due to machine set operation can be formulated easily.

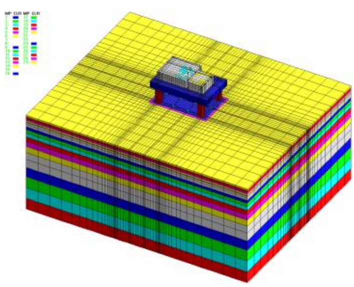

Fig.1 Computation model.

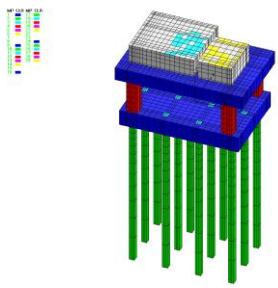

Fig.2 Computation model.

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The description of seismic excitation of the analyzed system is complicated. The numerical solution of dynamic responses using available advanced software presents no problem. Repeated computations allow generalized conclusions.

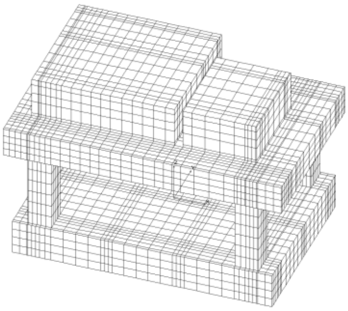


Fig.3 Computation model.

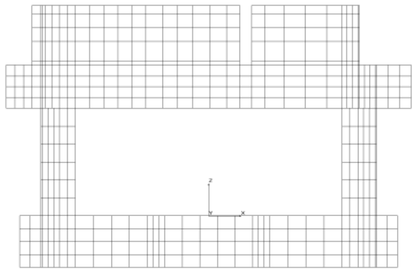


Fig.4 Computation model.

As to the presented case of the foundation design, several variants of the foundation structure have been designed, and several repeated computations of dynamic responses of that structures have been carried out in order to find optimum dimensions of the foundation structure. The relevant clauses of the standards, codes and regulations have been considered. With respect to the subsoil properties, pile foundation has to be used. The analyses described in the paper concern the final foundation design.

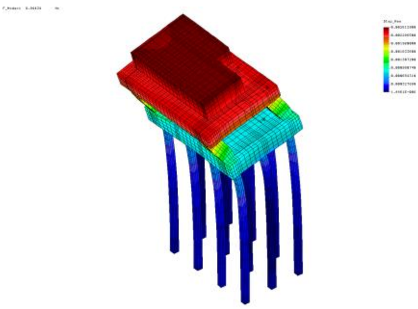


Fig.5 Normal mode of vibration, $r = 1$.

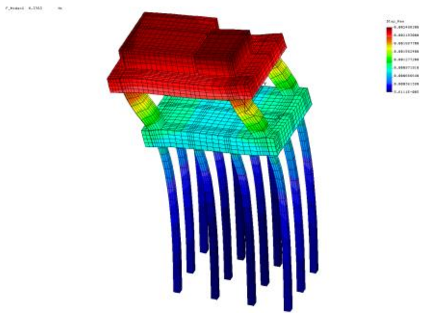
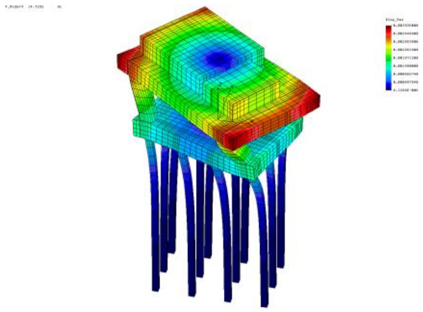


Fig.6 Normal mode of vibration, $r = 2$.

Description of the analyzed structure

The foundation structure design assumes the top slab with dimensions 9420 mm x 5900 mm x 1000 mm supported by four columns (800 mm x 800 mm) 2510 mm high, fixed on the embedded base slab with dimensions 8800 mm x 5900 mm x 1200 mm. There are designed twelve precast reinforced concrete square piles (400 mm x 400 mm) 11500 mm long, regularly placed over the base slab bottom.

The machine set comprises the steam turbine as the driver and the centrifugal compressor as the driven machine. The nominal speed of the machine set rotors equals 10583 rpm (i.e. 176.4 Hz), however the full operating range 8391 rpm up to 11641 rpm (i.e. 140 Hz up to 194 Hz) should be considered. The nominal mass of the operating machine set equals 33845 kg. The machines of the set are mounted on separated steel baseplates, anchored by bolts in the upper slab of the foundation structure.



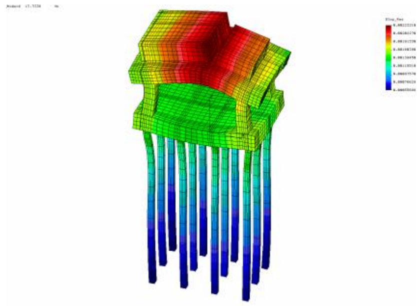
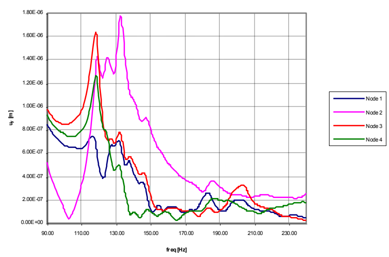


Fig.7 Normal mode of vibration, ***r = 3.*** **Fig.8** Normal mode of vibration, ***r = 4.***

Vibrations of the foundation structure excited due to rotor unbalances at normal steady state operation should comply with the criteria given in standards (DIN 4024 - Part 1; ISO 1940-1:1986; API Standard 617, 2002; SNIP 2.02.05-87; ISO 10816-1:1995) or specifications. The effective values of velocities of vibration of the compressor baseplate should not exceed $v_{eff} = 4.5\ mm.s^{-1}$. The turbine baseplate vibration should not exceed the peak-to-peak displacement value of $8\ \mu m$ within an extended speed range (5926 rpm - 13969 rpm). Consequently, the values $v_{eff} = 4{,}14\ mm.s^{-1}$, $v_{max} = 5.85\ mm.s^{-1}$, $s_{eff} = 2.83\ \mu m$ and $s_{max} = 4.00\ \mu m$ can be considered as conservative limits for foundation top slab steady state vibrations.



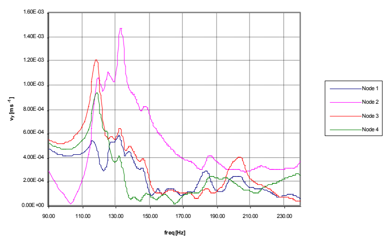
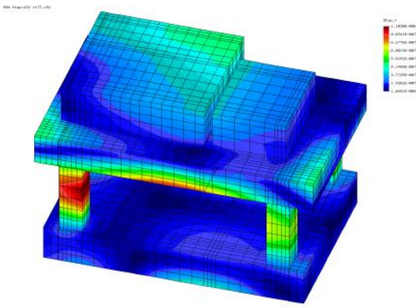


Fig.9 Relations $u_y(f)$. **Fig.10** Relations $v_y(f)$.

Computation models of the structural system

For the dynamic response analysis of the foundation structural system a computation finite element model has been developed using the COSMOS/M version 2.85 program package. The model has been developed as a combination of spatial structures modeling the machinery, reinforced concrete table top type foundation structure, reinforced concrete piles and soil body.

The machines with baseplates have been modeled using SHELL4, SOLID and MASS finite elements. Concentrated masses and elements with appropriately selected computation material densities have been used so as to approximate the spatial mass distribution specified by the positions of mass centers of machines. The anchoring system has been modeled using BEAM3D and flat SOLID elements. The reinforced concrete foundation structure with the integrated piles has been modeled as an isotropic homogeneous continuum using SOLID finite elements. Material properties specified in the standard material database have been used.



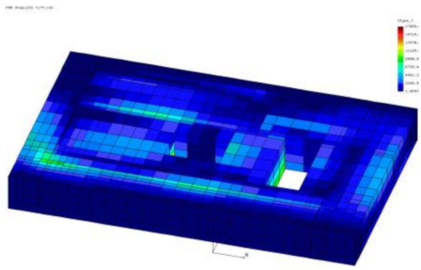
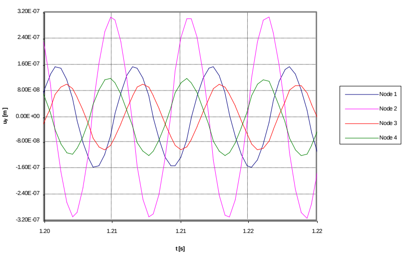


Fig.11 Field of displacements $\boldsymbol{u_y}$.　　**Fig.12** Field of stresses $\boldsymbol{\sigma_y}$.

The selected soil body has been modeled as a horizontally layered continuum. The properties of the soil in a layer have been selected in accordance with the detailed study of geological and geotechnical site conditions as follows: $\boldsymbol{G_{dyn} = (50 + 2h)\ MPa}$ (with soil depth h in [m]), $\boldsymbol{\nu = 0.49}$, $\boldsymbol{\rho = 1980\ kgm^{-3}}$. Inside the layers the soil has been modeled as an isotropic homogeneous continuum, using SOLID finite elements. The boundaries of the soil body have been placed in sufficient distances from foundation. At the soil body boundaries, the corresponding coinciding nodes have been mutually constrained. Considering the loading of the soil and the value of the coefficient of adhesion/friction, no relative displacements of the soil-foundation bottom or soil-pile side contact surfaces have been assumed. Lateral soil support of embedded foundation base slab has been modeled in a simplified way. The soil layer in contact has been modeled using a low soil shear modulus value.



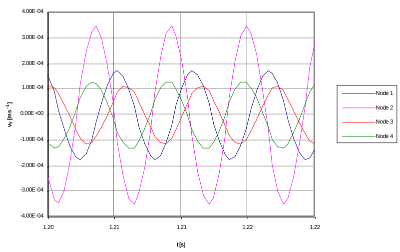


Fig.13 Displacement $\boldsymbol{u_y(t)}$.　　**Fig.14** Displacement $\boldsymbol{v_y(t)}$.

The mechanical energy dissipation in the complex pile foundation structural system is not well investigated. The relevant standards state, that the damping shall typically be determined by tests. Otherwise, empirical formulae may be used. In the given case relations given in SNIP 2.02.05-87 could be applied. The effective damping ratios vary between 0.20 and 0.06, dependent on the mode of vibration. According to DIN 4024 - Part 1, conservative effective values of damping ratios ***0.02*** should be applied.

It should be noted, that the application of professional programs requires frequently particular formulation of damping. In the given problem, using the direct integration computation procedure, the mechanical energy dissipation in the structural system has to be modeled using Rayleigh proportional damping coefficients. Coefficient values $\boldsymbol{\alpha(K) = 2.597e\text{-}5}$ and $\boldsymbol{\beta(M) = 12.46}$ have been computed assuming for the whole structure average material damping ratio 0.02. Since the structural system is strongly non-homogenous, the selection of alfa and beta values has been checked by evaluating effective damping ratios from responses of the model to force impulse loading. Values of effective damping ratios ranging from 0.01 up to 0.05 have been found. Damping ratio 0.02 has been assumed for computations using the modal expansion procedure.

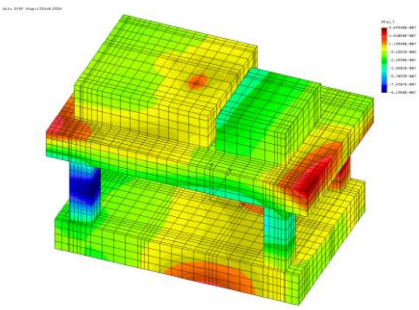


Fig.15 Fields of displacements $\boldsymbol{u}_y$.

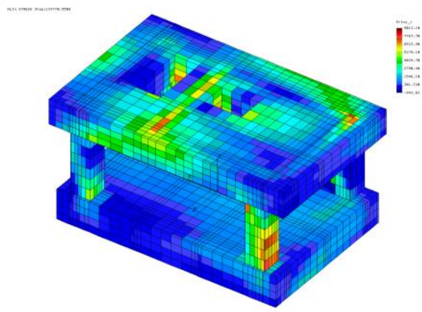


Fig.16 Fields of stresses $\boldsymbol{\sigma}_y$.

The computation model has been developed using 60540 finite elements localized by 63117 nodes with 178675 degrees of freedom. The computation model is shown in Figs. 1, 2, 3, 4.

Three alternatives of the model have been analyzed: model A with very low soil density, model B with nominal soil density and model C with rigid soil.

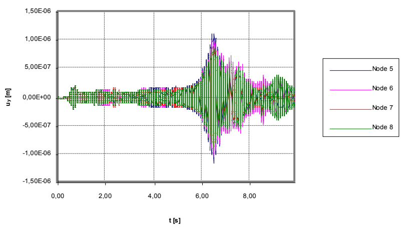


Fig.17 Start-up $u_y(t)$.

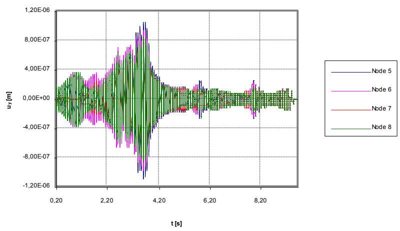


Fig.18 Shutdown $u_y(t)$.

Computation models of loads

Steady state conditions

At steady state operation with nominal frequency of rotation f = 176.4 Hz, the vibration of the foundation structure is excited by two rotating forces due to unbalanced rotors of machines. The rotating force vectors Fk (k = 1 - turbine, k = 2 - compressor) are inputted into computation by force component time histories in the following form:

$Fkz(t) = + Fk.\cos(2\pi.f.t + \alpha kz)$ (k = 1, 2)

$Fky(t) = + Fk.\cos(2\pi.f.t + \alpha ky)$ (k = 1, 2)

Three design situations have been considered, namely normal operation conditions (F1 = 1.6 kN, F2 = 14.52 kN), operation conditions with increased rotor unbalances and malfunction conditions (F1 = 2.24 kN, F2 = 20.4 kN). The exciting forces for operation with increased rotor unbalances have been specified so that the assumed vibration response would just activate the monitoring system to send an alarm signal. The exciting forces for malfunction conditions have been specified so that the assumed vibration response would just activate the monitoring system to send a shutdown signal.

At all analyzed cases, three configurations of exciting forces have been considered:

L;C1: all forces are in the same phase

LC2: forces are shifted in phase by π/2

LC3: forces are in opposite phases

Transient state conditions

The courses of forces due to rotor unbalances appearing during the start-up as well as during the shutdown of the machine set have been computed assuming constant angular acceleration of rotors. Thus, the following time histories of forces have been used:

Start-up: $0 \leq t < t1$:

Fkz(t) = + Fk.b1(t).cos(φ1(t) + αkz) *(k = 1, 2)*

Fky(t) = + Fk.b1(t).cos(φ1(t) + αky) *(k = 1, 2)*

b1(t) = (t/t1)2

φ1(t) = π.f.t2/t1

Steady state: $t1 \leq t \leq t2$:

Fkz(t) = + Fk.b2(t).cos(φ2(t) + αkz) *(k = 1, 2)*

Fky(t) = + Fk.b2(t).cos(φ2(t) + αky) *(k = 1, 2)*

b2(t) = 1

φ2(t) = 2π.f.t - π.f.t1

Shutdown: $t2 < t \leq t3$:

Fkz(t) = + Fk.b3(t).cos(φ3(t) + αkz) *(k = 1, 2)*

Fky(t) = + Fk.b3(t).cos(φ3(t) + αky) *(k = 1, 2)*

b3(t) = ((t3-t)/(t3-t2))2

φ3(t) = (π.f)/(t3-t2)(t1.t2-t1.t3 -t22+2.t3.t-t2)

Natural frequencies and modes of vibration

For the response analysis 300 natural frequencies and normal modes of vibration of the foundation structure model A have been computed. Two lower frequencies are as follows:

f1 = 8.94 Hz - dominate displacements y

f2 = 9.38 Hz - dominate displacements x

Four selected normal modes of vibration are presented graphically in Figs. 5 up to 8 for illustration. The figures show the complexity of the vibration modes.

For the B-model 550 natural frequencies and modes of vibration have been computed. Two lower frequencies:

f1 = 4.77 Hz - dominates torsional displacement rz

f2 = 5.02 Hz - dominate displacements x

For the C-model 300 natural frequencies and modes of vibration have been computed. Two lower frequencies:

f1 = 14.64 Hz - dominate displacements y

f2 = 14.95 Hz - dominate displacements x

The differences in computed values show the importance of establishing a correct computation model for the dynamic analysis of the foundation structure.

According to applicable standards (DIN 4024 - Part 1; SNIP 2.02.05-87) the vibration behaviour of the foundation structure can be assessed using the criteria based on natural frequencies. Taking into account the specified machine set speed limits, the spectrum of natural frequencies of the foundation structure should generally avoid the range 112 Hz - 214 Hz.

The performed modal analyses have shown, that at all models the most significant group of twelve lower natural frequencies ranges from 5 Hz up to 60 Hz. Still in the range from 112 Hz up to 214 Hz, there have been computed up to 161 natural frequencies (indeed most of them with negligible effective modal masses). It is obvious, that the simple criterion of natural frequencies cannot be satisfied.

The relevant clauses in the applicable standards (DIN 4024 - Part 1; SNIP 2.02.05-87) state that, if the vibration behaviour of the foundation structure cannot be adequately assessed using the criteria based on natural frequencies, an analysis of forced vibrations of the structure is required on the basis of excitation forces declared by the machine manufacturer. Consequently, such an analysis has been performed.

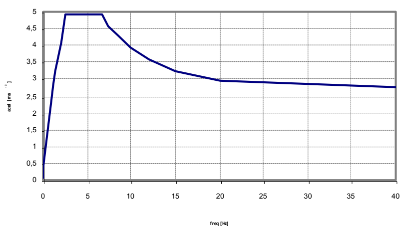


Fig.19 Design spectrum.

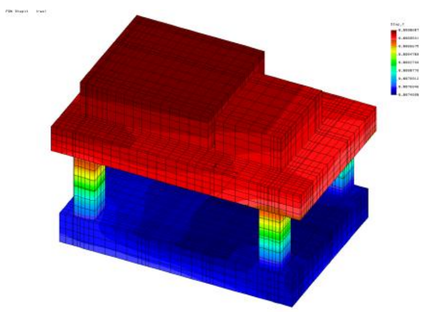


Fig.20 Seismic response E2 ($\boldsymbol{u_y}$).

Steady state responses of the foundation structure -extended operating range

The steady state responses of computation models A and C to the action of the set of rotating forces due to unbalances (LC1, LC2, LC3) have been computed using the mode expansion procedure. The responses (RMS-values) have been computed for frequencies of rotation stepwisely changed within the extended operating range. Thus, the relations "vibration displacement vs. frequency of rotation" have been obtained. Similarly, the relations "vibration velocity vs. frequency of rotation" as well as the relations "vibration acceleration vs. frequency of rotation" have been obtained. Constant effective modal damping ratio 0.02 has been used. The computed relations allow to assess the general dynamic behaviour of the foundation structure.

For illustration, plots uy(f) as well as vy(f) are presented for the two nodes 1, 2 of the turbine submodel as well as for the two nodes 3, 4 of the compressor submodel (see Figs. 9 and 10). All nodes lie on the shaft line. The computation of fields of response quantities is illustrated by Fig. 11 (transversal displacements uy at f = 177.19 Hz with instantaneous maximum of 1.103 μm) and Fig. 12 (stress components σy of the top slab at f = 177.19 Hz with instantaneous maximum of 17959 Pa).

Vibrations at nominal speed steady state operation conditions

The steady state responses of computation models at nominal speed conditions to the action of forces due to unbalanced rotors have been computed by direct numerical integration of equations of motion. Three design situations have been considered, namely normal operation conditions, operation conditions with increased rotor unbalances and malfunction conditions. At all analyzed cases, three configurations of exciting forces have been considered (LC1, LC2 and LC3). Ultimate limit states of the foundation structure have been analyzed using relevant clauses of the applicable standard prEN 1992-1-1 (2003).

For illustration of the behaviour of the model A (LC2), selected sections of time histories of vibration displacements uy and velocities vy are presented in Figs. 13 and 14 for the four nodes 1, 2, 3, 4 of the machine set models.

The computation of fields of response quantities is illustrated by Fig. 15 (transversal displacement uy at t = 0.5528 s with instantaneous maximum of 0.465 μm) and Fig. 16 (stress components σ1 at t = 0.5508 s with instantaneous maximum of 9012 Pa).

Transient responses of the structure

The transient responses of the foundation structural system to forces due to rotor unbalances appearing during the start-up as well as during the shutdown of the machine set have been computed using direct numerical integration of equations of motion of the computation models A, B and C. A short time interval of steady state operation has been inserted between the start-up and shutdown phases in order to get nearly steady state initial conditions. At all analyzed cases, three configurations of exciting forces have been considered (LC1, LC2 and LC3).

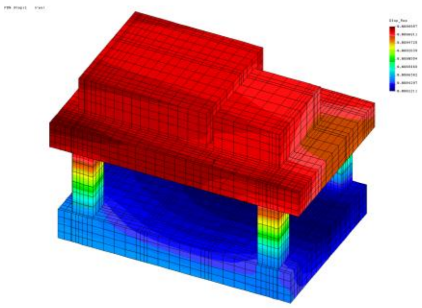


Fig.21 Seismic response E2 ($\boldsymbol{u_{res}}$).

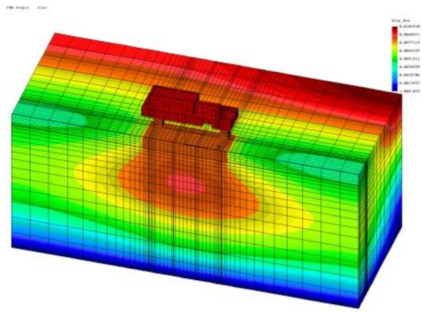


Fig.22 Seismic response E2 ($\boldsymbol{u_{res}}$).

For the model A with exciting forces configuration LC2, the time histories of vibration displacement components $\boldsymbol{u_y(t)}$ during the start-up are presented in Fig. 17 for the four corner nodes of the foundation top slab upper surface. The time histories $\boldsymbol{u_y(t)}$ during the shutdown are shown in Fig. 18.

Foundation response to seismic excitation

The seismic excitation of the computation model inputted on the soil boundaries has been assumed to be uniform, defined by the design horizontal acceleration spectrum specified for the site (see Fig.19). As for the vertical seismic excitation, the intensity has been considered as two thirds of the horizontal one. Component seismic responses EX, EY, EZ have been computed by the linear response spectrum method considering all computed natural frequencies and normal modes of vibration of the model. The response quantities have been combined using the SRSS rule. The component responses have been combined using the linear (100%, 30%, 30%) rule to find the three extremes (E1, E2, E3). The resultant response has been computed as E = max (E1, E2, E3).

For illustration, the fields of computed extreme displacements of the model B (without soil body) for the case E2 are shown in Fig. 20 (uy – transversal displacement values in the range from 7.49 mm to 9.06 mm) and Fig. 21 (ures resultant displacement values reaching 9.89 mm). The sectional view of the field of computed extreme displacements of complete model B for the case E2 is shown in Fig. 22 (ures resultant displacement values reaching 10.28 mm).

Foundation serviceability assessment

The effective values of amplitudes of vibration displacements of the foundation top slab computed for normal operation conditions within the specified extended speed range are less than seff = 1.91 μm. The peak values of vibration displacement are less than smax = 2.70 μm. The computed effective values of vibration velocities are less than veff = 1.58 mm.s-1. The peak values are less than vmax = 2.24 mm.s-1.

Referring to Sect.2, it can be concluded that the designed table top foundation structure satisfies the specified vibration criteria:

seff	= 1.91 μm	<	seff(lim)	=	2.83 μm
smax	= 2.70 μm	<	smax(lim)	=	4.00 μm
veff	= 1.58 mm.s-1	<	veff(lim)	=	4.14 mm.s-1
vmax	= 2.24 mm.s-1	<	vmax(lim)	=	5.85 mm.s-1

The seismic response analysis has predicted the extreme response displacement of the compressor baseplate smax = 376 μm, i.e. 94 x smax,LIM. Compared with the computed unbalance excitation responses, the seismic response is very high. However, no relevant criteria have been specified.

Conclusion

Extended numerical study of dynamic responses of a table top type foundation structure for a centrifugal compressor has been carried out using finite element model variants. The design of the foundation structure has been optimized to comply with the vibration criteria stated in technical specifications relevant for the compressor operation. The study has shown the importance of the seismic response analysis of the foundation structure. The seismic response may be essential for assessing the vibrational behaviour of the foundation. The numerical results of performed analyses have proved, that the computation model has to be developed very carefully.

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References

[1] DIN 4024 - Part 1: Machine foundations. Flexible structures that support machines with rotating elements. 1988.

[2] DIN 4024 - Teil 2: Maschinenfundamente. Steife (starre) Stuetzkonstruktionen fuer Maschinen mit periodischer Erregung. 1991.

[3] ISO 1940-1:1986: Mechanical vibration - Balance quality requirements of rigid rotors. Part 1: Determination of permissible residual unbalance. 1986.

[4] Arya, S.C., O°Neill, M.W. & Pincus, G. (1979): Design of Structures and Foundations for Vibrating Machines. Houston, Texas, Gulf Publishing Company.

[5] Axial and Centrifugal Compressors and Expander-compressors for Petroleum, Chemical and Gas Industry Services. API Standard 617. July 2002.

[6] SNIP 2.02.05-87: Foundations of Dynamic Load Machines. Construction Codes and Regulations. USSR State Building and Construction Committee. Moscow 1988.

[7] prEN 1992-1-1: 2003 (E). Eurocode 2: Design of concrete structures - Part 1.1: General rules and rules for buildings. Nov. 2003.

[8] ISO 10816-1:1995: Mechanical vibration - Evaluation of machine vibration by measurements on non-rotating parts - Part 1: General guidelines. 1995.